DFIG-Based Wind Power Conversion With Grid Power Leveling for Reduced Gusts

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***Abstract*—This paper presents a new control strategy for a grid-connected doubly fed induction generator (DFIG)-based wind energy conversion system (WECS). Control strategies for the grid side and rotor side converters placed in the rotor circuit of the DFIG are presented along with the mathematical modeling of the employed configuration of WECS. The proposed topology includes a battery energy storage system (BESS) to reduce the power fluctuations on the grid due to the varying nature and unpredictability of wind. The detailed design, sizing, and modeling of the BESS are given for the grid power leveling. Existing control strategies like the maximum power point extraction of the wind turbine, unity power factor operation of the DFIG are also addressed along with the proposed strategy of "grid power leveling." An analysis is made in terms of the active power sharing between the DFIG and the grid taking into account the power stored or discharged by the BESS, depending on the available wind energy. The proposed strategy is then simulated in MATLAB-SIMULINK and the developed model is used to predict the behavior. An effort is made to make the work contemporary and unique, compared to the existing literature related to issues governing grid fed DFIG-based WECS.**

***Index Terms*—Battery energy storage system (BESS), doubly fed induction generator (DFIG), grid power leveling, vector control, wind energy conversion system (WECS).**

I. Introduction

THE use of renewable sources for electric power generation has experienced a huge face lift since the past decade. Increased economical and ecological woes have driven researchers to discover newer and better means of generating electrical energy. In this race, wind energy conversion systems (WECS) have stood ahead of other renewable energy sources like solar energy, which still lags behind owing to high cost per kilowatt-hour (kWh) of electrical power generated. Overall, the contribution of these renewable energy systems to the power system has been increased rapidly from the last two decades [1]. Among all the available technologies for WECS, the doubly fed induction generator (DFIG) is most accepted because it combines the advantages of reduced converter ratings for power conversion and an efficient power capture due to the variable speed operation.

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Variable speed operation of electric generators is arguably more advantageous [2], [3] compared to the fixed speed counter parts (using asynchronous generators without power electronic interface). The widely preferred topologies for the variable speed operation are the conventional asynchronous generators with rated power converters, the permanent magnet synchronous generators (PMSG's) with rated power converters, and the DFIG with partial rating power converters (slip power rating).

Among these, a WECS integrated with a DFIG is the most popular option to harness wind energy due to varying nature and unpredictability of the wind speeds. A DFIG-based WECS offers advantages of improved efficiency, reduced converter rating, reduced cost and losses, easy implementation of power factor correction, variable speed operation, and four quadrant control of active and reactive power control capabilities [4], [5]. Due to variable speed operation, total energy output is 20%–30% higher in case of DFIG-based WECS, so capacity utilization factor is improved and the cost per kWh energy is reduced.

Generally, the stator windings of the DFIG are directly connected to the grid and the rotor windings are fed through bidirectional PWM voltage source converters (VSCs) to control the rotor and stator output power fed to the grid for variable speed operation [6], [7]. It is possible to control rotor current injection using fully controlled electronic converters to ensure effective operation in both sub- and super-synchronous speed modes [6]. Decoupled control of active and reactive powers using the vector control is already discussed in detail by researchers [8], [9]. In a DFIG, both the stator and the rotor are able to supply active power, but the direction of this power flow through the rotor circuit is dependent on the wind speed and accordingly the generator speed. Below the synchronous speed, active power flows from the grid to the rotor side and rotor side converter (RSC) acts as the voltage source inverter while the grid side converter (GSC) acts as a rectifier but above the synchronous speed, RSC acts as the rectifier, and GSC acts as the inverter. The converter handles only around 25% of the machine rated power while the range of the speed variation is $\pm 33\%$ around the synchronous speed [6]. An effective control strategy addresses the dynamics of a DFIG-based variable speed wind turbine and the operation of the converters under subsynchronous and super-synchronous modes of operation and during the transition period of these two modes.

Although, DFIG has proven to be a viable solution for high-performance WECS, grid connectivity is still a serious issue owing to the varying nature and unpredictability of wind speeds. The power output is highly fluctuating due to the same ($\pm 100\%$

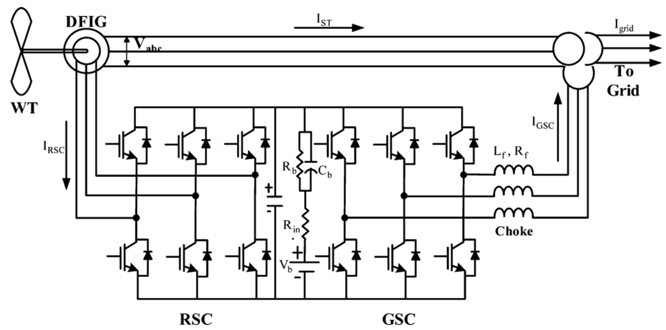

Fig. 1. DFIG-based WECS with a BESS (Thevenin's equivalent) in dc link for grid power leveling.

fluctuations on daily basis as shown in Fig. 2 and Table I and lower magnitude fluctuations in hours/minutes/seconds basis). Incorporating a battery or any other energy storage device in the dc link enables temporary storage of energy and, therefore, the ability to provide constant output active power, which is both deterministic and resistant to wind speed fluctuations [9]. This topology is explored in this paper and a novel control strategy to ensure "power-leveling" at the grid side is proposed. It can be argued over the selection of an energy storage system for higher rating WECS, but a detailed study on large-scale energy storage utilities is presented in [10]–[12]. Battery systems are employed for systems having ratings as high as 10 MW [13]. The WECS configuration used in this work (DFIG with converters cascade and a battery energy storage system (BESS) in the dc link) is shown in Fig. 1.

In this paper, a mathematical model for a grid connected DFIG is developed using back-to-back connected PWM-VSCs with a BESS in the dc link. Moreover, a detailed design procedure to select the rating of the BESS is also described by considering real-time data. The proposed "grid power leveling" control strategy is implemented in a stator flux oriented system, also taking into account other issues governing the satisfactory operation of a DFIG, viz., unity power factor operation of the machine, optimized active and reactive powers transfer, and tracking the maximum power point of the wind turbine.

II. Proposed Configuration and Principle of Operation

Fig. 1 shows a schematic of the DFIG with the rotor and grid side converters (RSC and GSC), a BESS in the dc link and a transformer and a choke (optional) in the rotor circuit. The BESS in the dc link is shown by its Thevenin equivalent [14], [15]. A configuration without the transformer in the rotor circuit (which accounts for the stator-rotor turns ratio of the DFIG) has also been reported in some literature. However, when the transformer is connected, the choke used for smoothening the currents of the GSC can be eliminated as the transformer leakage reactances would be sufficient enough for the cause. The rotor winding inductances act to smooth the currents of the RSC. This topology supports the complete control of the active and reactive powers of the system with the rotor and grid side converters around 33% (nearly one-third) of the rated speed [6]. Hence, the converters used for this topology are to process only the slip power which is 25% to 35% of the overall machine rating.

The principle of operation of this topology for grid power leveling is that, by incorporating a battery in the dc link, a constant power is fed to the grid always. The average power for a given place (where the wind turbine is installed) is calculated from the available wind speeds and this calculated average power is fed to the grid to reduce the power fluctuations on the grid. At the higher wind speeds (and the machine operating at super-synchronous speed), power output of the WECS is higher as compared to the average power and, therefore, the extra power is stored in the battery. In contrast, at the lower wind speeds (and the machine operating at subsynchronous speed) the power is drawn from the battery to maintain the average power fed to the grid. Thus it is ensured that the power fed to the grid is always "leveled," resulting in an efficient and reliable source of electrical power to the grid.

III. Design Issues in Proposed WECS Configuration

Since wind energy is a nonreliable and unpredictable source of energy varying from time to time, stringent conditions are to be imposed in designing the proposed configuration of a WECS using DFIG with a BESS. Choosing the appropriate rating of the battery is of utmost importance as any discrepancy would lead to malfunctioning of the system. The major issues in designing the wind turbine and the BESS are as follows.

A. Design of Wind Turbine

The output power of the turbine and the wind velocity has the nonlinear relation. The output power of the turbine is given by the following equation [16]:

$$P_m = 0.5 * C_p(\lambda, \beta) * \rho A v^3 \tag{1}$$

where C_p is power coefficient, ρ is air density, A is swept area of rotor blades, v is the wind- velocity, λ is the tip speed ratio, and β is the pitch angle.

The power coefficient is defined as the power output of the wind turbine to the available power in the wind regime. This coefficient determines the "maximum power" the wind turbine can absorb from the available wind power at a given wind speed. It is a function of the tip-speed ratio (λ) and the blade pitch angle (β). The blade pitch angle can be controlled by using a "pitch-controller" and the tip-speed ratio (TSR) is given as

$$\lambda = \frac{\omega R}{v} \tag{2}$$

where ω is the rotational speed of the generator and R is radius of the rotor blades.

Hence, the TSR can be controlled by controlling the rotational speed of the generator. For a given wind speed, there is only one rotational speed of the generator which gives a maximum value of C_p, at a given β. This is the major principle behind "maximum-power point tracking" (MPPT) and a wind turbine needs to be designed keeping this strategy in mind.